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SENSORCRAFT MISSION SIMULATION STUDY

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The attributes of a high altitude, long endurance (HALE) intelligence, surveillance, and reconnaissance (ISR) unmanned aerial vehicle (UAV) are explored through mission simulations. Two mission level studies were conducted to develop baseline CONcepts of OPerations (CONOPS) of a concept vehicle referred to as SensorCraft.

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SensorCraft Mission Simulation Studies

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ABSTRACT

The attributes of a high altitude, long endurance (HALE) intelligence, surveillance, and reconnaissance (ISR) unmanned aerial vehicle (UAV) are explored through mission simulations. Two mission level studies were conducted to develop baseline CONcepts of OPerations (CONOPS) of a concept vehicle referred to as SensorCraft. The first study was a virtual simulation focused particularly on the vehicle parameters that affect air vehicle survivability. Two different missions each on two different days of a theoretical campaign were exercised. The second study was conducted as a constructive simulation building upon the results of the first through implementation of vehicle self-protect and radar cross section (RCS) characteristics. The study examined the effect of various sensor and vehicle parameters on the radar performance measured in terms of ISR specific Measures of Effectiveness (MOE) for ground targets. The second study used a high fidelity radar representation for ground moving target indication (GMTI) and synthetic aperture radar (SAR). Both studies demonstrated the war fighting potential of the SensorCraft concept and provided a valuable baseline for future CONOPS refinement. Additionally, valuable insight was gained into the specific technologies necessary to transition the SensorCraft concept from model to reality.

1. INTRODUCTION

With the success of ISR UAVs, specifically Global Hawk and Predator, in OPERATION ENDURING FREEDOM, it is apropos to consider how the potential operational utility of these vehicles can be maximized. As with all weapon systems, optimal effectiveness is achieved through a combination of capabilities and tactics, the development of which is the end goal of these analyses. The SensorCraft concept is an Air Force Research Laboratory technology portfolio showcasing new capabilities for the next generation of airborne ISR UAVs. Technical management of the portfolio is spearheaded by the Sensors and Air Vehicles Directorates with their key technologies which are enabled by but technologies being developed in the Propulsion, Materials & Manufacturing, Human Effectiveness, and Information Directorates.

However, to ensure military utility is maximized, the correct technologies need to be first developed and then integrated into a platform for which suitable CONOPS are developed. The purpose of this paper is to present the methodology used to create an initial set of SensorCraft CONOPS. This was accomplished by first specifying a set of design attributes for an ISR platform incorporating new technologies. The relative contribution of these new technologies was then quantified by exercising the vehicle in two separate mission simulation environments. The first simulation was focused on air-to-air engagements to attempt to measure the survivability of the SensorCraft against airborne threats. The second was focused on finding and tracking targets on the ground to measure the relative contribution of the selected sensory attributes to SensorCraft's effectiveness in obtaining a complete picture of a battlefield.

The analysis plan was designed in two phases so as to gain insights from multiple perspectives. The survivability study was conducted using a real-time virtual simulation environment that included pilots flying in both offensive and defensive roles, thereby giving Warfighter perspective and experimental uncertainty to the experiments. The software program used for this phase is called Man-In-the-Loop Air-to-Air System Performance Evaluation Model (MIL-AASPEM) and a more detailed explanation of its functionality and parameters can be found at the website, http://bahdayton.com/surv1/milaaspem. Conversely, the mission effectiveness study was run as a series of constructive simulations in the Joint Integrated Mission Model (JIMM). This versatile software framework supports both constructive and virtual experiments into which various digital or manned players can be programmed and exercised. The interested reader will find more information on the JIMM environment at http://www.hanscom.af.mil/esc-cx/JIMM/default or in reference [1]. The combination of constructive and virtual simulations is complementary and very powerful. From the virtual simulation uncertainty is introduced and researchers can receive immediate Warfighter feedback on vehicle tactics. This information can be incorporated into the constructive model, which is only limited by the physical constraints of the computational platform (speed of the processor, number of processors, amount of memory, etc) and can experiment with many different configurations of a new system involving a number of attributes within reasonable time constraints. Constructive simulations can also be used to identify opportunities for

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virtual simulation, where human intervention and decision-making are needed. The result is an efficient examination and reduction of a large, multi-dimensional trade space, leading to more specific designs that can be further evaluated using more costly virtual simulations.

In summary, the research approach called for tactics to be captured using virtual simulations and then conducting constructive simulations to produce statistically significant trade studies and identify further virtual simulation needs. Section 2 of this paper presents the survivability study background and results. Results from the mission effectiveness study are presented in section 3. A discussion of conclusions and a brief overview of future simulation work are presented in Section 4.

2. SURVIVABILITY STUDY

The objective of the survivability study was to quantify the relative contribution of various mission and vehicle parameters to SensorCraft's ability to successfully prosecute its mission in a hostile environment. To begin to answer this question, the analysis plan called for exercising SensorCraft in a total of four scenarios, created from two distinct missions on two different days of a hypothetical campaign. For each of the four scenarios, variations were made to selected vehicle and mission attributes. Data for several indicators of SensorCraft survivability were collected and analyzed, thereby gaining understanding of the relative importance of the various parameters.

The survivability study was conducted under the title of High Value Asset Attack (HVAA). The scenario used a notional campaign against an adversary assumed to possess a sophisticated integrated air defense system, high performance aircraft, and advanced cruise missiles. Against this peer adversary, two separate missions emphasizing Air Moving Target Indication (AMTI), namely Strike Escort (SE) and Defensive Counter Air (DCA), were executed on the first and fifth days of the simulated conflict. The SE mission called for friendly (Blue) forces to attack a single specified ground target 150 nautical miles into hostile (Red) territory. During this mission, SensorCraft was tasked to provide locations and types of Red threats and targets, which included the surface-to-air missile (SAM) sites and the ground control intercept (GCI) radar, to the Blue force strike package as it accessed the target area. The duty of SensorCraft in the DCA mission scenario was to detect inbound Red aircraft and cruise missiles, providing Blue aircraft with the information necessary to defend the friendly air space by intercepting the enemy targets. In both scenarios, SensorCraft's primary function was to provide the Blue forces with off-board sensor information, yielding more complete situational awareness of the air battle. A graphical representation of the various HVAA scenarios is shown in Figure 2.1.
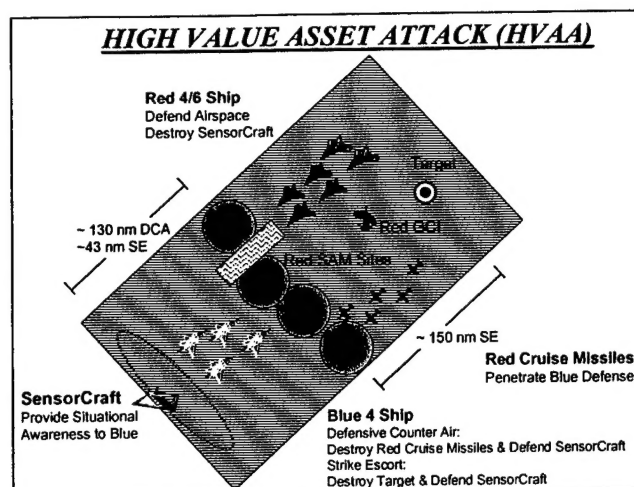

Figure 2.1—Survivability study scenario.

The goal of the survivability study was to determine first order values for vehicle and mission attributes and operational concepts to feed into the subsequent mission effectiveness study. The mission attribute varied for the survivability study, called setback, is the distance from Red territory where SensorCraft would operate. Choosing values for this parameter is always a compromise: as SensorCraft flies closer to the battlefield, it can see more of Red territory, but the danger of being shot down also increases. As part of the overall goal, the study sought to define the optimal compromise in setback distance, however during the simulations it became apparent that for the air-to-air scenarios selected for the study, the setback distance was of negligible importance. For this reason, setback distance was incorporated as an experimental variable in the second study.

The HVAA study varied two vehicle parameters, including two levels of ability for SensorCraft to protect itself through various measures and the RCS of the vehicle. Whereas setback distance helps define sensor suite performance requirements, self-protection and RCS influence vehicle design specifications. Figure 2.2 shows the design of experiments matrix used in the study. The other two variables in the matrix, number of aircraft and day of the war, specify the characteristics of the mission scenarios rather than vehicle specific parameters.

Run	Setback	Blue v Red A/C	Day	Self-Protect	RCS
	43	4 v 6	1	N	lo
	43	4 v 6	1	Y	vlo
	43	4 v 6	5	N	vlo
	43	4 v 6	5	Y	lo
	130	4 v 6	1	N	vlo
	130	4 v 6	1	Y	lo
	130	4 v 6	5	N	lo
	130	4 v 6	5	Y	vlo
	43	4 v 4	1	N	vlo
	43	4 v 4	1	Y	lo
	43	4 v 4	5	N	lo
	43	4 v 4	5	Y	vlo
	130	4 v 4	1	N	lo
	130	4 v 4	1	Y	vlo
	130	4 v 4	5	N	vlo
	130	4 v 4	5	Y	lo

Figure 2.2—Pressure contours around the cylinder.

Figure 2.3 shows a representative plot of typical composite results. For each of the four mission scenarios, each Red aircraft had ten air-to-air missiles with which to

shoot down SensorCraft. The chosen survivability metric is the percentage of shots fired compared to the number of SensorCraft destroyed. From Figure 2.3, it is readily apparent that the percentage of Red kills of SensorCraft is very low, even when the number of hostile aircraft is increased.
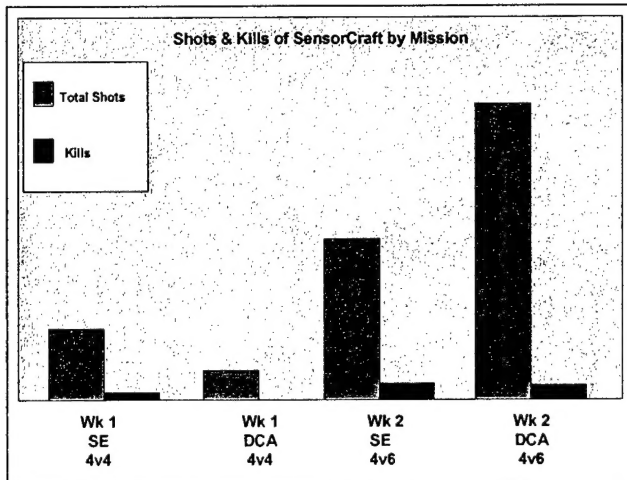

Figure 2.3—Number of SensorCraft killed by Red aircraft.

In order to gain as much data as possible, the study was purposefully designed to favor the Red forces. To this end, the red aircraft were increased to six versus the four Blue aircraft. Secondly, the Blue forces were given additional mission requirements to attack the ground target or the cruise missiles in addition to defending SensorCraft, whereas the Red forces had the single-minded pursuit of its destruction. Finally, the Red forces were armed with ten air-to-air missiles while the Blue aircraft had only four, creating a nearly four-to-one armament ratio. These conditions coupled with an experience factor among the pilots, more expertise for Red forces, created an environment where the probability of SensorCraft being destroyed was purposefully increased to collect as much data as possible.

The wealth of information gleaned from the HVAA study showed that having the ability to provide for self-protection was the most critical attribute to the survival of SensorCraft. Examples of self-protection systems currently in use on fielded aircraft include: radar warning receivers, towed decoys, flares, and infrared counter measures to name a few. The composite effects of self-protection measures were modeled in the simulation through each individual missile's probability of kill (P_k) value. As Figure 2.2 suggests, self-protection was an all or nothing proposition, where the effect of having self-protection lowered the P_k value by more than 85 percent.

Interestingly, the data showed that in these scenarios, the RCS values of the SensorCraft, whether low or very low, had only a small effect on the survivability of the SensorCraft. This result is due to several factors, including the SensorCraft orbit being beyond the reach of the SAM sites, the lack of SensorCraft maneuvering, and the lack realistic rules-of-engagement (ROE) for the Red pilots.

The way the different missions were designed, with SensorCraft flying a static racetrack orbit at a large distance from Red territory, it was never within range of the SAM sites where the RCS would have had a greater impact. Another artifact of SensorCraft's static racetrack orbit is that there was no intelligent maneuvering possible. By coupling radar and flight control technology, an aircraft can decide what aspect of its RCS to show to threats, but this capability was not included in the study. Finally, the RCS attribute was diminished in importance by the freedom accorded to the Red pilots to attack SensorCraft. Realistic ROE would have precluded Red pilots from operating with a priori knowledge of the operating altitude and setback distance of SensorCraft.

3. GROUND SURVEILLANCE STUDY

Whereas the survivability study sought to examine SensorCraft attributes related to the AMTI function, the ground surveillance study examined how effectively SensorCraft could detect and track mobile and stationary ground targets. In this study, the ground surveillance was accomplished by modeling a radar system working in the X-band frequency range. However, the radar simulation tools needed to model the GMTI and SAR sensor modes to a first-order level of accuracy did not exist in JIMM. Therefore, the effort initially focused on development and incorporation of high fidelity representations of the radar modes into the mission level model. In addition to developing the sensor modeling capability, a scenario database with high fidelity renderings of multiple types of ground vehicles had to be created to credibly test the sensor performance.

Within the JIMM simulation package, the SensorCraft vehicle is modeled as simply a point mass with the defining characteristics being RCS and three-degree-of-freedom aerodynamic performance. Although this simplified representation of the air vehicle is sufficient for the purposes of the mission effectiveness analyses, a very detailed and accurate representation of the SensorCraft radar performance is crucial. Specifically, modeling of the sensor suite's GMTI and SAR radar modes must be to a very high level of fidelity. Inasmuch as the existing radar functionality resident in JIMM was determined to be inadequate for this study, the radar development group in the Air Force Research Laboratory devised a methodology to obtain a high fidelity mission level radar model without inordinately increasing the computational burden. This was accomplished by modifying the variables within the radar range equation resident in JIMM to be more agile through creation of look-up tables to dynamically change values of clutter and jammer loss.

Radar engineers at Rome, New York used the Bi-static RAdar Development Simulation (BRADS), a physics-based radar propagation computer code, to obtain radar performance in terms of clutter loss data for a broad range of designated azimuths, elevations, and target clutter types. The dynamic nature of radar signal degradation is a

function of the altitude, range, and azimuth angle of the sensor platform with respect to the target, and also certain target characteristics such as RCS, radial velocity, and background clutter type. Linear interpolations of the BRADS data sets were used to populate a radar performance look up table. This process, referred to as meta-modeling (see Figure 3.1), allows high fidelity radar modeling at much faster run times, in real-time if needed.
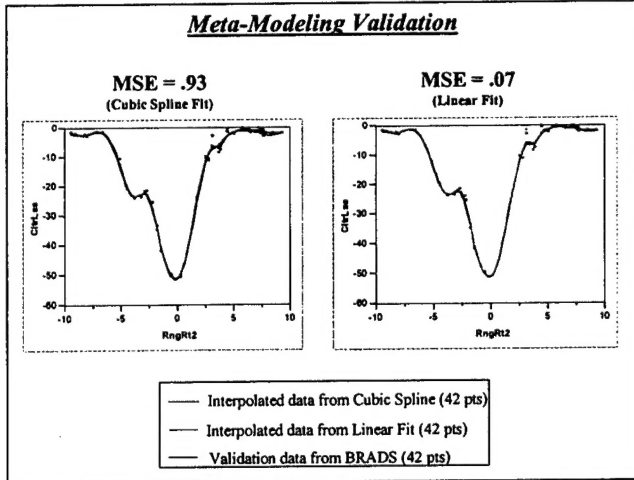

Figure 3.1—Validation of meta-model process.

JIMM employed these dynamic clutter loss estimates as an input to the standard radar range equation, from which can be derived a signal to interference plus noise ratio, SINR, as shown in equation 3.1.

$$SINR = \frac{K \times \sigma \times L_i}{R^4 \times L_{jp}} \qquad (3.1)$$

The factors that contribute to the value of SINR are a composite power factor (K), the RCS of the target (σ), the interference loss (L_i), the sensor-to-target range (R), and the jammer processing loss (L_{jp}). The interference loss is calculated as shown in equation 3.2, where the clutter and jammer to noise ratios combine to reduce the interference loss value.

$$L_i = \frac{1}{\dfrac{C}{N} + \dfrac{J}{N} + 1} \qquad (3.2)$$

The composite power factor captures the performance of the antennas, where the variability of the different antenna lengths is found in the receive gain factor, as shown in Figure 3.2.

K – Factor Description		
$K = \dfrac{P_{AV} \times G_T \times G_R \times lam^2 \times n \times G_{PC}}{(4p)^3 \times k \times T_0 \times F_n \times B \times t \times f_p \times L_s}$		
Parameter	**Description**	**Value**
P_{AV}	Average Power	9.5 kW, 39.78 dB
G_T	Transmit Antenna Gain	34.00 dB
G_R	Receive Antenna Gain	20 ft Ant = 43.90 dB 30 ft Ant = 45.66 dB
lam^2	Wavelength Squared	.99mm, -30.01 dB
n	# Pulses Coherently Integrated	60, 17.78 dB
G_{PC}	Pulse Compression Gain	26.99 dB
$(4p)^3$	Self Explanatory	32.98 dB
k	Boltzmann's Constant	-228.60 dB
T_0	Standard Temperature	24.62 dB
F_n	Noise Figure	4.50 dB
B	Bandwidth	70.00 dB
t	Pulse Width	-43.01 dB
f_p	Pulse Repetition Frequency	33.01 dB
L_s	System Losses	11.27 dB

Figure 3.2—K factor description and explanation.

The SINR ratio and an assumed probability of false alarm (10^{-6}) are fed into a sixth-order polynomial to produce a probability of detection (Pd) measure. The Pd then compared a draw from a uniform (0-1) distribution to determine if the target is detected or not. Of those targets detected, a track is assumed and a confusion matrix is employed to determine if correct or incorrect target identification has been made. If the identification is correct, that target can be assigned to a strike aircraft.

The scenario utilized for the ground surveillance study was fully populated with ground clutter and target types. In JIMM, the Generic Composite Scenario-build 10 (GCS-X) is used to represent missions on day 10 of the conflict with a focus on deep interdiction of mobile tactical ballistic missile (TBM) launch systems. The TBM systems have to ability to relocate, launch their weapons and relocate again, making them an extremely difficult target to destroy due to the small window of engagement opportunity.

The study concentrated on a single SensorCraft covering the representative battlefield shown in Figure 3.3. The Ground Reference Coverage Area (GRCA) of the simulated battlefield measures 160 km deep by 180 km wide with SensorCraft operating at various distances from the Forward Line of Own Troops (FLOT) as specified in the initial CONOPS. In this scenario, the battlefield has been populated with 850 different targets (40 different types) modeled using appropriate geometry and RCS data. The military targets included various tracked and wheeled vehicles of several sizes. These mobile targets were prioritized for the scenario as follows: first mobile surface-to-air missile batteries, then the TBM batteries, and finally main battle tanks of the Red forces. Civilian vehicles, added to attain a measure of realism in terms of collateral damage probabilities and sensor processor task saturation, were modeled after generic vehicles such as school buses and passenger cars. The RCS tables for the many ground targets were generated from CAD models using the XPatch program. The realism of the scenario was again

increased by inclusion of various background clutter types and electronic signal jamming practiced by the Red forces.
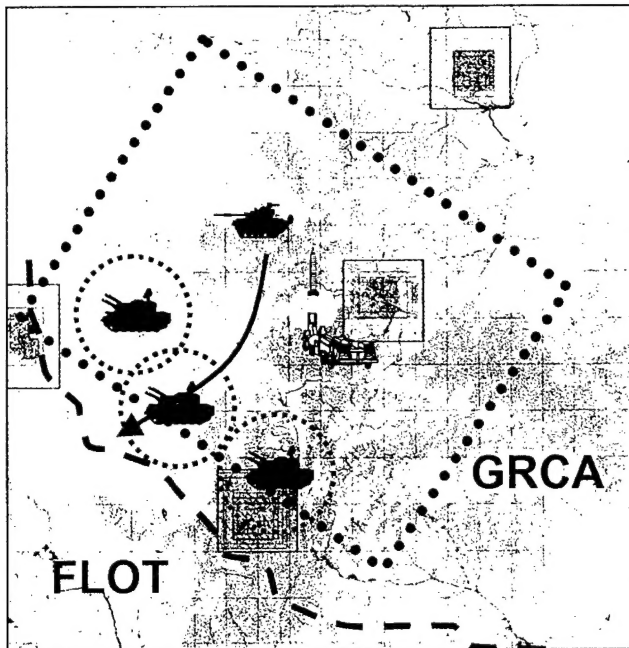

Figure 3.3—Representation of ground battle scenario.

Combining the high fidelity sensor suite model with the challenging simulation environment created a very realistic arena in which to test the SensorCraft capabilities. A test matrix was designed to focus the study on the sensor suite attributes having the largest impact on mission performance. It was determined that one of the most important factors for SensorCraft mission performance were the Concept of Operations (CONOPS) dictating flight profiles that affect range and angle parameters (azimuth, and elevation) to the targets. By operating SensorCraft in a fixed racetrack orbit at 65,000 feet altitude, the range and angle to all targets can be determined by the single variable of standoff distance.

In addition to mission performance, the ground surveillance study looked at three factors related to sensor performance: K-factor (see Figure 3.2), revisit rate, and antenna length. As explained previously, the K-factor is a measure of the antenna power and is a strong indicator of its projected performance. Antenna length is another strong indicator of anticipated sensor capability, and coupled with the K-factor forms the basis for vehicle design trades of wing length and engine power requirements. Revisit rate measures how often an area is scanned to update the battlefield picture. The clutter associated with different environmental backgrounds weighed heavily in the ability to track the targets. Table 1 shows the variations of attributes that were employed.

Table 1—SensorCraft Design Attributes of Interest

K-Factor	High – medium – low
Antenna Length	20 – 30 ft
Revisit Rate	15 – 30 sec
Clutter Type	Desert – Rural – Urban
Standoff Distance	50 – 90 km

All factors were measured to determine relative influence on the overall mission success, which was evaluated against established ISR measures of effectiveness (MOEs), specifically, the average time each target was able to be tracked after being identified.

The constructive simulations produced statistical data that can be sorted to examine specific attributes. Figure 3.4 shows data divided first by antenna length and then by K-factor level (low-med-high). The percent change between the low and medium levels of power is much greater than between the medium and high levels for both antenna lengths, indicating diminishing returns for increased antenna power. The revisit rate associated with this data is 15 seconds.
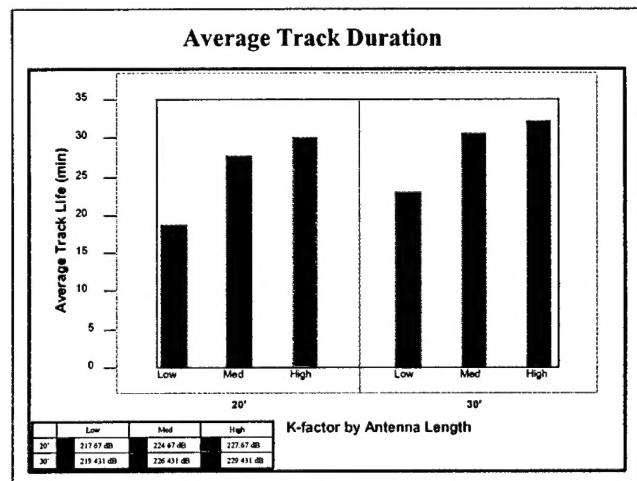

Figure 3.4—Track life as a function of antenna length.

Figure 3.5 shows the same data as in Figure 3.4, this time compared against the 30-second revisit rate. The same diminishing return trend is evident irregardless of revisit rate.
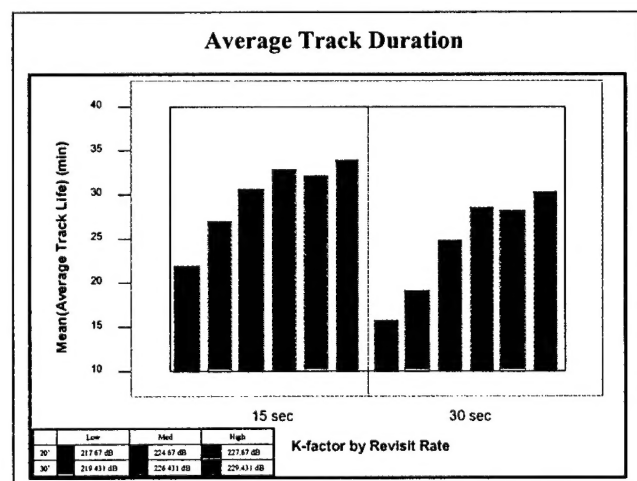

Figure 3.5—Track life as a function of revisit rate.

Interestingly, although for lower power antennas the 15-second revisit rate has nearly double the track life of the 30-second revisit rate, the performance differential diminishes as the antenna power increases. While Figure

3.5 gives an inkling that this is true, the trend is clearly evident in Figure 3.6, where revisit rates for each antenna power and length are graphed adjacent to each other.
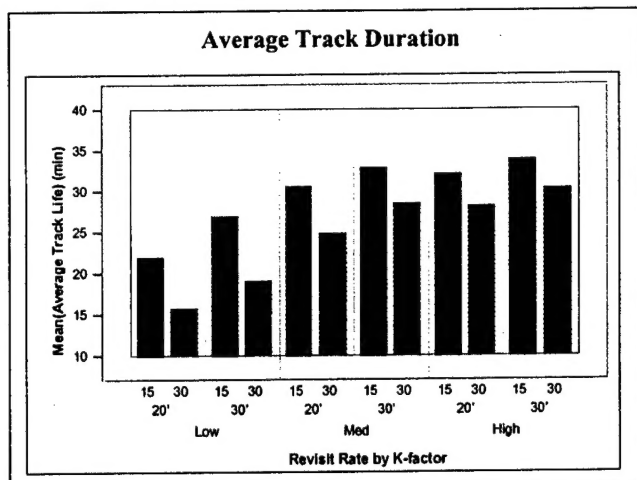
Average Track Duration

Figure 3.6—Average track life as a function of K-factor.

The effect of electronic signal jamming, modeled simply as a reduction to the P_d for the entire sensor system, is shown in Figure 3.7. The SensorCraft parameters used for this case were 15-second revisit rate, rural clutter, 20-foot antenna, 90-kilometer standoff distance, and high level K-factor.
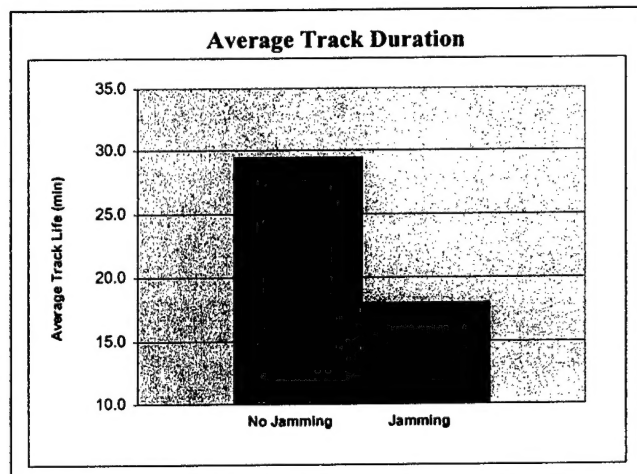
Average Track Duration

Figure 3.7—Effect of jamming on track duration.

The numerous attributes selected to be examined within this study made 72 combinations possible. The results presented herein are representative composite data that provide important insight into absolute and relative importance of the five factors. The study showed that more length and power is always better than less, however, it is interesting to note that more length and less power (orange bar in Figure 3.5) were better than less length and more power (teal bar). This information would indicate that the engine power extraction could be reduced in exchange for making the wings or fuselage where the antenna resides larger.

4. CONCLUSIONS

The combination of virtual and constructive mission simulations has produced the data required to select the preliminary vehicle attributes and CONOPS for a baseline SensorCraft. The key to achieving this goal was recognizing the most critical design requirements and building an analysis plan to specifically address those portions of the trade space.

One of the goals of the SensorCraft concept is to develop a multi-function sensory capability on a single platform. Therefore, the constructive simulation will be expanded in the future to include UHF GMTI and SAR radar modes following the meta-modeling methodology developed for the ground surveillance study. A high fidelity representation of the AMTI radar mode will be developed subsequent to the UHF modes. Once all of these modes are developed, a sensor mode control system will be incorporated into the simulation environment.

In conjunction with the expanded constructive simulations, a parallel study will be conducted in a virtual simulation environment, with the goal of refining SensorCraft CONOPS around the expanded sensor suite. The mission will be focused on vehicle employment and data management for time critical targeting.

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[1]   J. P. Nalepka, "JIMM, The Next Step For Mission Level Simulation Models," Proceedings of the 2000 AIAA Conference; AIAA #2000-4491.